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"Study of Magnetic Resonance Sensitivity for Detection of Materials: Are Multiple Coil Arrays Better than Single Coils."
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1. The coupling between coils in an array is a concern. A bibliography of articles about the use of arrays for magnetic resonance is attached as appendix A. One principle concern is the mutual inductance and the "mutual resistance." Various schemes in the literature for dealing with these issues seem adequate at the moment. The effects of these couplings, plus also the mutual capacitance, may be worth a closer look in the future. There are several interesting alternative tuning schemes suggested which should be considered further.

2. An important consideration for magnetic resonance sensitivity is the coil quality factor, Q. Due to the proximity effect, coil Q varies with coil size. For single turn coils at fixed frequency, such as the prototypes for mine detection, coil Q appears to fall to zero for zero coil size. Details of a simple model calculations of the proximity effect for single turn coils are attached as appendix B. At 3 MHz, the reduction in Q due to the proximity effect is quite noticeable for the 10 cm to 30 cm diameter, copper "pancake" coils appropriate for mine detection. Hence, the proximity effect will ultimately limit the minimum practical size of coils used for an array.

3. An alternative method to achieve high Q would be to use a superconducting coil. The technology to create practical superconducting coils (for explosive detection) is in its infancy. The use of superconducting coils may be beneficial in the long run, however. Schiano (Penn State) has been working on a small, self-resonant, spiral-wound HTSC coil (approx 2" diameter, from Conductus), achieving loaded Q's of 500,000 at 3.5 MHz, more than 2 orders of magnitude larger than has been achieved for much larger copper coils. These very large Q's are much larger than the Q of the NQR signals (i.e. sigtnal Q = NQR line width divided by the NQR frequency) which is to be observed. These very large Q's will certainly result in measurement complications and may also result in some very interesting science and improved explosive detection. The use of superconducting coils as a component of the tuning circuit might also be of interest.

4. A simple calculation of the NQR sensitivity for an array of square-planar coils was developed. The results of several of these calculations are attached as appendix C. An issue to consider is the relationship between the direction of the RF magnetic field during the NQR excitation (i.e. the RF pulse), and the orientation of receiving coils. Using simple symmetry arguments, it is easy to show that the NQR response from *any* powder sample must be either identically zero or it mimics the RF excitation. That is, if the excitation is linearly polarized along the x-direction, the response will be a maximum for a receiving coil designed to pick-up linearly polarized signals along the x-direction, etc. This is particularly important for arrays and surface coils since the direction and magnitude of the RF excitation may not be uniform across the volume of interest (VOI).

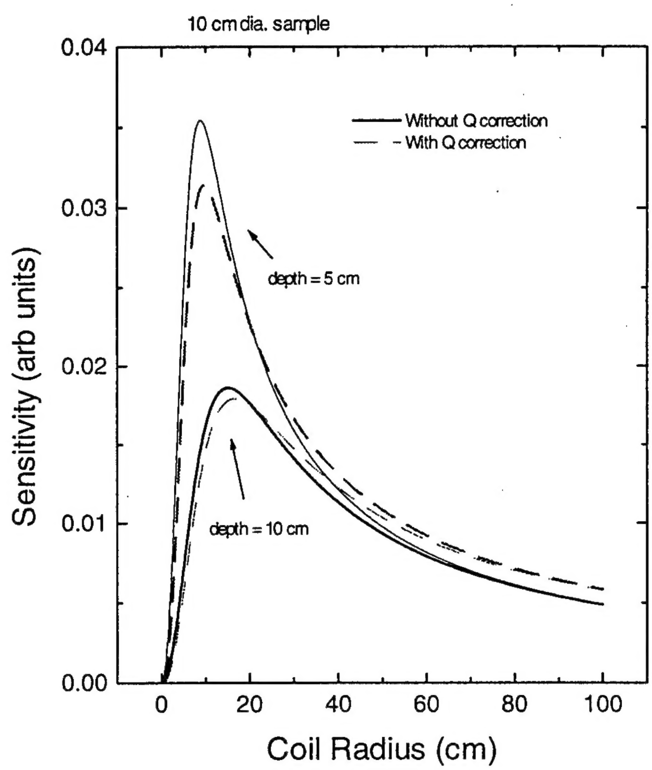
5. Many experimental measurements with coils of different sizes were made, confirming that the relative changes in Q from the calculations mentioned above are accurate. Most of these coils

were made from roofing copper (conductivity indistinguishable from "99.9" Cu). Details are attached as Appendix D.

6. When calculating the receive sensitivity of an array, there are two important limiting cases:
   (A) when the sample size is small or comparable to the size of the individual coils which make up the array and
   (B) when the sample size is comparable to (or larger than) the entire array.

Mine detection (using copper coils) will most likely be case (A). The detection of explosives in luggage or on a person could be either case (A) or case (B).

7. For case (A) one can, as a first approximation, assume all of the signal is picked up by one coil of the array. It is easy to show that for a given sample size and position (e.g. depth for a land mine) there will be an optimum size for single coil detection. The calculation is usually done by considering the strength of the magnetic field produced at the position of the sample by a unit current in the coil, and then using the principle of reciprocity. These results should be corrected by considering the changes in the coil Q (see (2) above), however for the case of land mine detection those corrections are small (Q varies relatively slowly with coil size). In practice, one often uses the calculated magnetic field at a single point at the sample position. For land mine detection this may be a bit severe. Instead one should integrate over the sample volume. Alternatively, one can simply consider the mutual inductance between the receiving coil and a coil at the sample position with a diameter roughly equal to the sample diameter. An example calculation using this mutual inductance approach is shown below.



For these calculations, Grover's tables (Grover, *Inductance Calculations*, 1973, chap 11) were used for a 10 cm diameter sample on axis with a circular detection coil and for excitation and

reception both along the axis of the coil. The relative vertical scale for calculations with and without the Q correction cannot be directly compared, however the vertical scales for similar conditions at different depths can be compared. (The effects of Soil losses on Q have not been included here).

For these practical dimensions, the optimum size of the coil is insensitive to the changes in Q with size. Clearly, however, if one wishes to simultaneously measure signals from such a sample located somewhere in a larger VOI, a very significant loss of sensitivity will result if one large coil is used rather than an array of (independent) optimally sized receiving coils. Or to put it another way, the gain in Q one gets with a larger coil does not make up for the loss of signal due to a smaller mutual coupling (i.e. a smaller "filling factor").

8. For case B (which might occur for sheet explosives in luggage), one can start with a similar argument to that in (7) above and determine that the optimum coil size will be comparable to the size of the sample. This is certainly true for detection by a single coil. However, the signals from multiple coils can be added together (since in this case, all will see roughly the same signal) and hence the answer is not quite so obvious.

A simple calculation, analogous to the one in (7) above, proceeds as follows. A large "sheet" sample (taken to be circular) of radius A, which is a distance d away from a receiver coil of radius a is considered. First, the optimum value for a is determined for single coil detection. Now that single coil is replaced by four coils covering the same area. The sensitivity of each of those coils a bit less than one fourth that of the original coil (it is 0.25 times the correction for the reduction in Q). Those signals (plus the noise from those coils) are added together and compared to the original single coil. A sample calculation follows:

Starting values:

Radius of (thin sheet) sample: 20 cm
Distance from coil: 20 cm

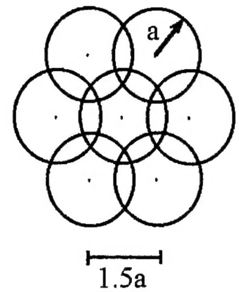
Computed values (includes Q dependence on size):

Optimum radius for single coil detection: 37.8 cm
Relative signal strength for that coil: 1.69
Noise level for that coil: 1 (by def'n)
Signal to noise for single coil: 1.69
Relative signal strength for 1/4th of the area: 1.69/4
Total signal from four such coils: 1.69
Total noise from four such coils: 2 (noise assumed uncorrelated)
Total signal to noise ratio for four coils: 1.69/2

Thus it appears that an array would not be particularly advantageous for case B. The actual situation is not as bad as this, however. In the calculation above, the noise from each coil was considered uncorrelated. By simply dividing a larger coil into smaller coils (with the sum of the areas of the smaller coils matching the area of the large coil), there will be a significant mutual

inductance between the coils, and hence the noise will be correlated.

The size of this effect can be estimated by considering a large hexagonal array of small circular coils, a portion of which is shown in the figure below. For co-planar circular filaments of radius a, with their centers spaced 1.5a apart,* there will be no mutual inductance between neighboring elements. To the extent that the mutual inductance between 2nd neighbors can be neglected, the noise from these coils will be uncorrelated. For each of the smaller coils, the total flux through that coil will induce an EMF giving rise to a signal. However,



the physical area per coil is reduced due to the overlap with adjacent coils. It is straightforward to show that

$$\frac{\text{Area of each coil}}{\text{physical area per coil}} = 1.4$$

and hence if we cover our original area with N of these coils, the total signal acquired will be roughly 1.4 times that of the single coil (assuming Q has not changed). The total noise will scale as $N^{1/2}$, which would imply a break even for N = 2 and a loss in sensitivity for N > 2 (though the flux gain is only 1.08 for 2 overlapping coils, not 1.4).

Hence, even taking this into account, there is good reason NOT to use an array for this case. An analogy can be made to understand this better. Suppose one wished to measure the length of a rod with a meter stick with markings accurate to (say) 1 mm. One could simply measure the entire rod and achieve an accuracy of ±1mm or one could divide the rod up into N pieces, measure the length of each piece, then add the results together. Assuming random errors, the length determined using the sum is then determined to an accuracy of $\pm N^{1/2}$ mm.

For measurements in an electrically conducting medium (such as moist soil or on a person) the effects of Q changes due to the medium will also need to be factored in. The loading will be much worse for the larger coil, and hence the use of smaller coils may be an advantage. Such has been found to be the case for some MRI measurements.

* Linear extrapolation from Grover's tables gives a value of 1.506 for circular filaments.

Appendix A - Bibliography

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Appendix B - Summary of Single-turn coil proximity effect calculations.

The finite-sized, single turn coils are modeled using N discrete wires with a circular cross-section, wired in parallel. Only circular coils are considered. Kirchhoff's laws give

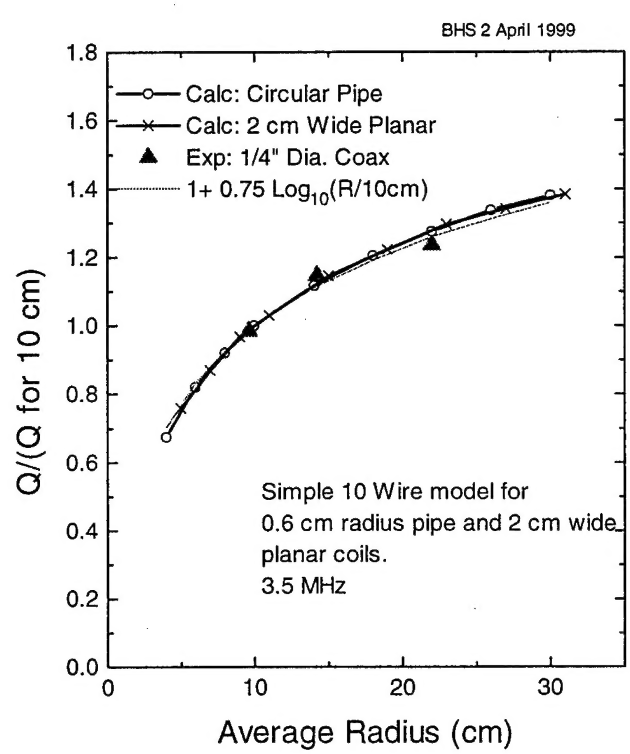
$$(i\omega L_l + r_l)I_l + i\omega \sum_{k \neq l} M_{kl} I_k = 1$$

where r_l is the resistance of wire l, and is proportional to the length of the wire and inversely proportional to the cross-sectional area of the wire, L_j is the inductance of wire j, and M_{kl} is the mutual inductance between wires k and l. L and M are computed by extrapolation from Grover's tables. These equations are solved and the total current is simply the sum of the currents through all of the coils. The impedance of the whole coil is then the inverse of the total current. The ratio of the imaginary part of the impedance to the real part yields Q. The individual currents can be used to investigate the current distribution in the coil.

Pancake single turn coils were investigated using co-planar wires with increasing radii. Coils made from large circular wire (e.g. 1/4" copper pipe or coax) are approximated with wires equally spaced around the circumference of the wire (due to the skin depth effect, the interior of the wire can be ignored).

The equation above was inverted using a simple Fortran program. This program worked well provided the number of wires was less than about 15. Numerical problems arise for a larger number of wires.

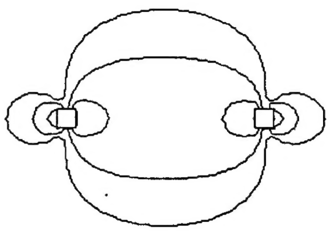
The results are summarized in the graph to the right. Since absolute calculations of Q are not particularly good using this technique (the resistivity of the wire is a parameter), results are scaled to a 10 cm coil. Also shown on this graph are some experimental points.



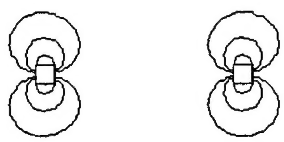
Appendix C - results of sensitivity calculations

Shown are ontours of constant sensitivity. Spacing between contours is approximately logarithmic (1,3,5,10 scale).

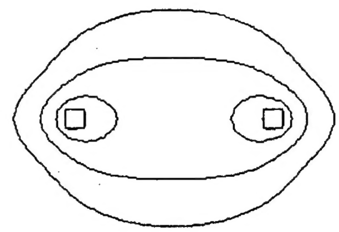
Receive Sensitivity depends on excitation- One (square coils) side-by-side (Z is toward the top of the page)



Excited along Z

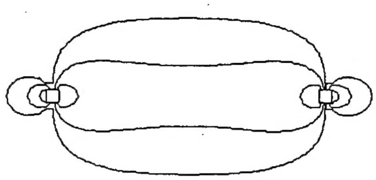


Excited along X

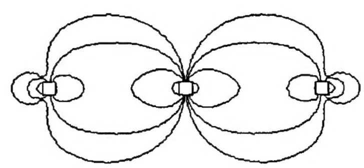


Excited by this coil

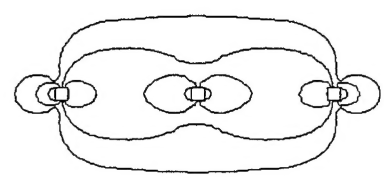
Receive sensitivity for multiple coils depends on how signals are combined. (Excitation along z used here).



Added In Phase
(Rectangle Coil)



Added Out of Phase
(Figure 8 Gradiometer)



Independent Detectors
(Optimized Phases)

Note that there is very little to gain when comparing a larger rectangle coil and the use of two independent coils of equal area. The configuration with the highest Q will give the best sensitivity.

Appendix D - Selected Coil Measurement Results

Square Planar Coils made with 3M copper tape on plexiglass sheet

Outside dim. (cm)	Inside dim. (cm)	C (pF)	Resonant f (MHz)	Q
28.9	23.8	2200	4.35	277
26.85	23.8	2200	4.11	229
16.0	13.0	2200	5.94	220
16.0	13.0	2530	5.55	197
16.0	13.0	4400	4.19	190
16.0	11.0	4400	4.92	219
16.0	11.0	4730	4.75	220
10.7	5.7	4730	7.045	181

Rectangular Planar Coils made from 3M copper tape on plexiglass - tape Width same as last coil in previous table - outside dimensions shown.

Length (cm)	Width (cm)	C (pF)	Resonant f (MHz)	Q
22	10.7	4730	4.87	197
22*	10.7	4730	4.75	164

* 2nd coil here is wired as a figure 8 coil.

Figure-8 split-gap coil from layers of roofing copper (left at NRL)
Two circular elements, 10 cm i.d., 18 cm o.d., next to each other, wired as figure-8.

C (pF)	Resonant f (MHz)	Q
none added	13.487	600 ± 10
2200	5.435	390
4400	4.003	390
5500	3.601	405
5720	3.538	395

“Split-C coil” - layers of C-shaped elements stacked, which opening alternating by 180 deg.
(Elements are square, from roofing copper, 0.010" teflon spacing,)

Layers	Self-Reson. Freq (MHz)	Q (unloaded)
3	13.53	1100
5	9.361	690
7	7.666	680
9	6.739	630
11	6.159	550

Using a single one of these square elements, with a capacitor (ATC)
Compare to similar elements with different materials.

Material	C added (pF)	Reson. f (MHz)	Q
Cu	2200	7.197	395
Cu	3300	5.867	445
Cu	4400	5.096	450
Cu	5500	4.58	440
Brass	5500	4.60	340
Cu/Ni 705 alloy	5500	4.59	250
Cu (larger square)	4400	3.48	540

(Larger square has inside dim. 21 cm, outside dim 30.5 cm)

Using multiple elements bolted together (no insulator), slot aligned (looks at thickness effects)
5500 pf nominal capacitance for all (same capacitors used for all).

# layers	f	Q
1	4.589	500
2	4.628	498
4	4.694	493

Pancake-like coil made from co-planar windings of #18 copper wire, i.d. 22.4 cm, o.d. 25 cm, C = 4400 pF for all.

# wires used	f	Q
1	2.577	114
2	2.86	159
3	3.03	209
4	3.135	236
5	3.214	262
6	3.292	292
7	3.341	322
8	3.376	343
9	3.398	377
9 (parallel winding scheme)	3.46	385
Roofing Cu, same i.d. & o.d.	3.503	485

(Note: except as noted, winding scheme has wires cross, each wire spends equal time at all possible radii)

Coils from Litz Wire (from Wiretronic, inc, Calabasas, CA), single-turn circular

Coil ave. diameter	#wires/wire size	C (pF)	f (MHz)	Q
28 cm	420/44	2200	3.37	127
25.5	2730/40	2200	4.15	75
25.5	2730/40	3700	3.20	90
25.5	2730/40	5900	2.55	105

Slit-gap resonator from 1/4" semi-rigid coax, 28.3 cm ave diameter (circular). (compare to previous 20 cm coils of same construction)

C (pF)	f (MHz)	Q
2200	4.096	395
3300	3.338	408

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13. ABSTRACT *(Maximum 200 words)*

Receiver coil sensitivity for Materials Detection by magnetic resonance was investigated, comparing measurement strategies using one large coil and arrays of smaller coils. It is found that an array of smaller coils will besult in impproved sensitivity for detection of sample volumes which are small compared to the volume to be sampled, however one large coil will perform better for larger samples.

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